N94-16352

POSSIBLE DUST CONTAMINATION OF THE EARLY SOLAR SYSTEM

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Measurements carried out over more than twenty years indicate a deficiency of neutrinos emitted from the deep interior of the Sun in comparison with the neutrino flux expected from canonical solar models. The early measurements[1], were sensitive only to high-energy neutrinos emitted from ^8B on a minor branch of the energy-producing nuclear reactions in the solar interior. Thus these measurement were not widely considered to be a definitive test of solar physics. However the more recent measurements[2], which are sensitive to lower energy neutrinos, produced primarily by the p-p reaction on the main energy-producing branch of the solar nuclear reactions, pose a far more significant mystery in physics. One possibility is that the Sun's interior opacity is lower than expected due to a paucity of elements. This paper discusses the possibility that the Sun formed from material less abundant in heavy elements than usually believed, and the subsequent contamination due to the settling of surrounding dust brought the abundance of heavy elements—in the protoplanetary nebula, and in the Sun's convective envelope—up to the currently observed value.

Much recent speculation has focused on the possibility that the solar neutrino deficit results from previously unobserved aspects of neutrino physics, specifically the possibility that neutrinos undergo transitions to a form not observable in the the current detectors. This line of speculation has been given additional strength by the fact that the observations—especially the most recently observed p-p–neutrino deficit—now push solar models to extreme departures from standard conceptions about the Sun. However, at least one aspect of the observations is especially provocative, and suggests that serious consideration should be given to the possibility that it is the Sun, rather than the neutrinos, that might not conform to earlier ideas. The measured low-energy neutrino flux—approximately 80 SNU[2]—seems to correspond closely to the minimum neutrino production consistent with the solar luminosity, regardless of the solar model. If the cause of the solar neutrino deficit were a result of neutrino physics alone—having nothing to do with the Sun—then this correspondence would stand as a truly remarkable coincidence.

It has been known that such a low neutrino flux could be explained if the temperature in the Sun's core were substantially lower than the approximately $1.5 \cdot 10^7$ K central temperature given by standard solar models. Such a low central temperature could occur if the solar interior were depleted in the so-called metals—atomic species heavier than helium—resulting in lowered internal opacity. In such a case, the chemical abundances measured in the solar convective zone would be unrepresentative of the deep-interior abundunces. The chemical composition of the Sun is measured spectroscopically using light emitted from the outer layers, and by analyzing solar-wind atoms, which are emitted from the Sun's main-sequence star.

Compositional measurements made at the solar surface must apply to the entire convection zone, i.e. to the outer 30% by radius and 2.5% by mass, which is well mixed. However, it is not equally clear that the composition of the inner, radiative interior matches that of the convection zone, as little material mixing may occur between these two zones. Energy-producing nuclear reactions are concentrated near the center of the Sun, with virtually all of the nuclear reactions and all of the energy production confined within the inner 25%. Assuming that little mixing has occurred between convective-zone and core material over the lifetime of the Sun, the question of radial compositional gradients devolves largely to questions associated with the formation of the Sun—and especially to whether star-formation processes might produce stars with significant radial compositional gradients.

Dust settling from outer regions of a molecular cloud core could result in contamination of the nebula and the outer layers of the Sun. In a quiet (nonturbulent) molecular cloud core with radius 10^{17} cm, the time-scale of settling of grains with radii $r_d = 10^{-4}$ cm, and time scale of the settling $\tau_s \sim 10^7$ yrs. The presence of even weak turbulence, with velocities $v_t > v_{pg}$ results in mixing that overwhelms the

C-7

settling of small dust particles. Observations show that molecular clouds, in general, and their cores, particularly, reveal internal chaotic motions with nearly a Kolmogorov spectrum[3]. The characteristic velocities of these turbulent motions are $v_t \sim 10^4$ to 10^3 cm s^{-1}, i.e. the turbulence is subsonic in the scale of core size ($\sim 10^{17}$ cm, $c_s \simeq 3 \cdot 10^4$ cm s^{-1}), but the velocity exceeds the settling speed of small dust particles gas through the gas. We do not expect that such small particles could settle effectively before collapse.

However turbulence causes relative motion of nearby particles, promoting collisions that can be followed by coagulation.[4] A detailed study of the coagulation of grains in the molecular cloud cores is undertaken by Weidenshilling and Ruzmaikina (1993, see abstract for this conference).

$$\delta v_r \simeq \frac{t_k}{t_e} v_t.$$

where t_e is the characteristic time in which a grain changes its motion under the drag force of gas, v_t is the rms turbulent velocity of the gas, and t_k is the eddy time scale for the largest eddies. The equation of coagulation of the particles, assuming that each collision results in coagulation, gives

$$\frac{dm_d}{dt} = \sigma_d v_r n_d m_d,$$

where n_d is the number density of the dust grains in the cloud. Assuming that $n_d m_d = q\rho$ (where q is the mass fraction of the dust in comparison with the gas, and ρ is gas density) and that dust grains are spheres with the density independent of radius, the equation is integrated to give

$$r_d^{1/2} = r_{d0}^{1/2} + 27\, q \left(\frac{\rho}{\rho_d}\right)^{1/2} \left(\frac{v_t^3}{c_s\, l_t}\right)^{1/2} t,$$

where r_{d0} is the initial radius of the grains, l_t is a characteristic length scale of turbulent motions, c_s is the sound speed, and t is a time.

As long as grains grow, they can reach a size where the velocity of settling exceeds the turbulent velocity. After that the turbulence can no longer suppress the precipitation of grains. The ratio of the stationary velocity of settling of growing particles to the typical turbulent velocity is

$$\frac{v_{pg}}{v_t} \simeq \frac{6 \cdot 10^{-2}}{\beta} \left(\frac{q}{2 \cdot 10^{-3}}\right)^2 \left(\frac{t}{10^7 \text{ yrs}}\right)^2 \frac{\rho}{2 \cdot 10^{-19} \text{g cm}^{-3}} \frac{v_t}{c_s},$$

where is $\beta = l_t c_s / v_t R$. For illustration, we take the fraction of the condensible matter in the presolar material q to be 1/10 of the 'solar abundance'; this 1/10 is approximately the abundance of heavy elements in the solar core for the nonstandard solar models calculated by Bahcall and Ulrich[5], which could be consistent with the observed neutrino flux. One can see from this equation that even for $\beta \simeq 1$ the settling of solid particles becomes significant in a time scale $t \sim 3 \cdot 10^7$ yrs, provided the cloud turbulence speed is comparable to the speed of sound.

This paper discusses possible implications—for the formation of the protoplanetary nebula in particular as well as for the formation of stars and protoplanetary nebulae in general—of such preferential dust settling from the surrounding, unaccreted material in protostellar clouds.

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